

# MODELLING STAGE–DISCHARGE RELATIONSHIPS IN ANASTOMOSED BEDROCK-INFLUENCED SECTIONS OF THE SABIE RIVER SYSTEM

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## ABSTRACT

Flow dynamics in a bedrock-influenced river system, the Sabie River, South Africa, have been found to be significantly different from those in temperate alluvial systems. The lack of lateral water connectivity leads to multiple bedrock distributaries with varying water surface elevations across a cross-section. Distributary activation is dependent on upstream breaching of bedrock barriers between distributaries by rising discharge. Where measurement of individual stage–discharge relationships in each distributary was not possible, a ‘Multiple Stage’ model was developed to predict hydraulic conditions in each distributary, using a single measured rating curve and knowledge of individual distributary water surface elevations at a low flow. Use of the ‘Multiple Stage’ model has enabled realistic prediction of channel geometry and hydraulic variables, that accounts for the different stages found in bedrock-influenced sections, yet is not prohibitively data intensive. Predicted ‘Multiple Stage’ results for maximum depth and velocity demonstrate the vast improvement on modelling flow dynamics, when compared to the conventional assumption of a single stage representing the whole cross-section. © 1998 John Wiley & Sons, Ltd.

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## INTRODUCTION

River channel form and process in bedrock channels has generally been considered to be fundamentally different in character from alluvial rivers (Howard, 1980). However, most research concerning flow dynamics in open channels has been concentrated on temperate, perennial, alluvial rivers and much of this work was based on flume studies (Bathurst, 1985). Recently, bedrock-influenced channels have received research attention, particularly with regard to the explanation of the origin of observed bedrock morphology (Grant *et al.*, 1990; Wohl, 1992, 1993; Kale *et al.*, 1996). This study demonstrates results from the Sabie River, South Africa, which is, by contrast to temperate alluvial systems, a bedrock-influenced channel displaying varying degrees of sedimentation and has a highly variable discharge regime. As such, it contains several channel types that are poorly represented in geomorphological or hydraulic literature (van Niekerk *et al.*, 1995) and provides hydraulic situations where conventional approaches to quantifying channel geometry and hydraulic parameters do not adequately describe the observed flow dynamics.

Bedrock-influenced channel types are common on the Sabie River, with 80 per cent of the river within the Kruger National Park being classified as either bedrock pool–rapid (29.5 per cent), bedrock anastomosing (26 per cent) or mixed anastomosing types (24.5 per cent). The wide diversity of geomorphological units in bedrock-influenced reaches of the Sabie River provides for a large variety of riparian species and specific vegetation communities (van Coller and Rogers, 1996). Since flow in these areas is confined to bedrock, there is little subsurface water interconnectivity and vegetation is dependent on regular, local inundation. Recent drought periods in the Sabie River catchment have led to severe tree deaths in bedrock reaches, compared to the river as a whole (van Coller and Rogers, 1996), which demonstrates the vulnerability of these areas. Therefore,

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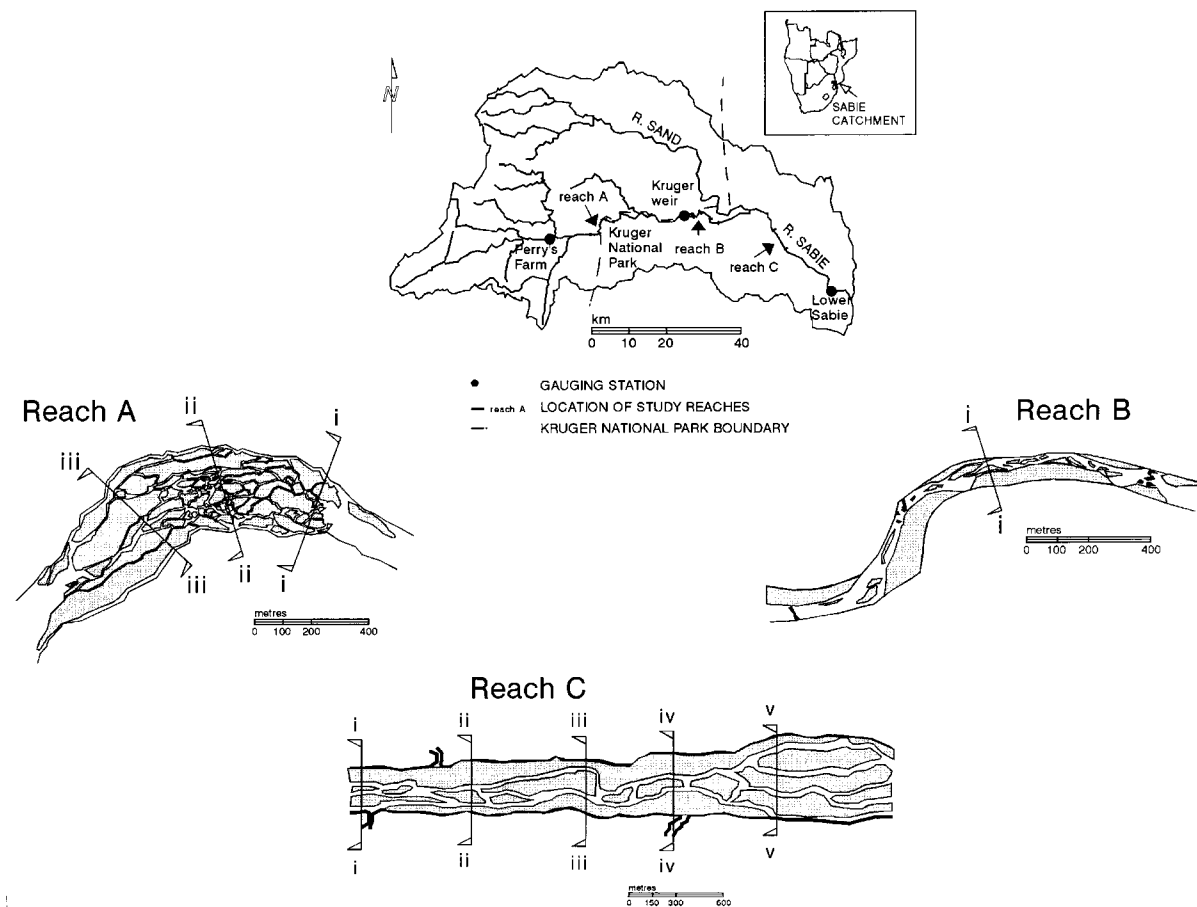


Figure 1. Location of the Sabie River and position of cross-sections used in this study. The flow direction is indicated by the arrows on the reach planform diagrams

realistic representation of flow parameters, such as velocity or hydraulic radius in these systems, is essential for accurate modelling of frequency of inundation of riverine habitats. Assessment of the implications for channel change in the geomorphologically and ecologically important bedrock-influenced reaches of the Sabie River, due to increased sediment input and flow abstraction, was desirable. Modelling of factors such as channel resistance and sediment competence for this purpose, required accurate base data on channel geometry and hydraulic parameters in these multiple-channel bedrock-influenced systems.

Wohl (1992) noted the need for more sophisticated models of channel hydraulics in bedrock-dominated systems in order to enhance the capacity for predicting sediment movement and consequent channel adjustment. In addition Moon *et al.* (in press) have highlighted the complex relationship that exists between the distribution of riparian vegetation and frequency of inundation in a bedrock-influenced river. This study aims to provide a model which allows for the more accurate prediction of a variety of indicators of flow dynamics and hydraulic conditions, operating in the relatively under-studied bedrock channel types encountered on the Sabie River.

### CHARACTERISTICS OF THE SABIE RIVER

The perennial Sabie River drains a 7096 km<sup>2</sup> catchment in the Mpumalanga Province, South Africa and Mozambique (Figure 1). Precipitation is concentrated in the summer months, from November to March, with

winter base flows at present supplied by the dolomitic aquifers in the mountainous areas to the west. Discharge patterns for the Sabie River reflect the variability of the rainfall and human influence.

The Sabie River catchment has been subject to uplift in the recent geological past (10 Ka to 100 Ka), resulting in incision into bedrock. This has generated a channel that has a 'floodplain' restricted by the width of incised bedrock. This feature has been termed the macro-channel by van Niekerk *et al.* (1995), as opposed to the smaller, active, perennially flowing channels and seasonally flooded features within its confines. The Sabie is a physically diverse river system that displays marked changes in channel type as the distribution of sediment over bedrock alters. A hierarchical river classification system has been developed by van Niekerk *et al.* (1995), outlining the five principal channel types found on the Sabie River, in the Kruger National Park, which represent stages in a continuum between fully bedrock through to fully alluvial channel types. Of these channel types, two are particularly influenced by the underlying bedrock: namely, bedrock anastomosing and mixed anastomosing channels.

Bedrock and mixed anastomosing channel types have been described on the Sabie River by van Niekerk *et al.* (1995) and on the Namada River, India, by Kale *et al.* (1996). Wohl (1992) describes inner channels, flanked by bedrock benches displaying relict channels and erosional features, which would act as distinct conduits for flow in flood conditions, in bedrock reaches of the Burdekin Gorge, Australia. On the Sabie River, bedrock anastomosing channel types have developed over areas of more resistant bedrock (Reach A, Figure 1). Chemical differences and joint and fracture patterns in the bedrock have generated resistant areas where the river is less able to erode vertically, leading to laterally widely spaced multiple distributary channels (Cheshire, 1996). The term 'distributary' is used in this study, although the individual channels concerned rejoin downstream and are strictly anastomosing channels. A large number of steep gradient (typical water surface slopes being up to 0.02) active bedrock distributary channels exist within the macro-channel. Sediment accumulation is restricted to lee bar deposits downstream of bedrock obstructions, low-energy zones and bedrock core bars on areas of elevated outcrops (van Niekerk *et al.*, 1995). Cross-sections through bedrock anastomosing channel types, therefore, have multiple distributaries active at winter low flows and these only join and flow as a single channel at rare, high-magnitude flood events (the entire macro-channel was inundated by a February 1996 flood of approximately  $1700\text{ m}^3\text{ s}^{-1}$ , but not during an earlier flood of discharge  $650\text{ m}^3\text{ s}^{-1}$ ). Seasonal distributaries become active only infrequently during the year, in response to elevated summer flows.

Increased sedimentation, due to increased sediment production in the catchment as a result of human influence, has led to a superficial cover of sand and silt over the bedrock at many sections of the Sabie River. Sedimentation is particularly pronounced downstream of the Sand River confluence (Figure 1). Mixed anastomosing channel types are characterized by mixed, alluvial and bedrock distributary channels that divide and rejoin over a distance much greater than the distributary width, within an alluvium-covered macrochannel (van Niekerk *et al.*, 1995) (Reach C, Figure 1). However, the underlying bedrock still exerts considerable influence on the channel form and hydraulics of these reaches.

#### DIFFERENCES IN CHANNEL HYDRAULICS BETWEEN ALLUVIAL AND BEDROCK MULTICHANNEL CROSS-SECTIONS

In alluvial sections (Reach B, Figure 1 and Figure 2a), where there is good water connectivity through the sediments, the water level in multiple channels, within a braided section of the Sabie River, was found to be the same at all discharges and a single stage–discharge relationship characterizes the whole section (Figure 2). However, in bedrock-dominated sections, where there is no lateral water connectivity, the water level in each distributary channel is dependent on the upstream conditions in that channel, so that a cross-section will contain channels with different water surface elevations. This was observed at all of the monitored bedrock-influenced cross-sections on the Sabie River, which had multiple channels active, at different elevations, at low and medium flows up to approximately  $1000\text{ m}^3\text{ s}^{-1}$ . Distributary activation is dependent on breaching of bedrock barriers between distributaries by rising discharges (Figure 3). Therefore, an increasing number of distinct distributaries become active as the water level rises and the elevation at which they become active is dependent on the local bedrock topography. This leads to different flow depth–discharge relationships for each distributary channel.

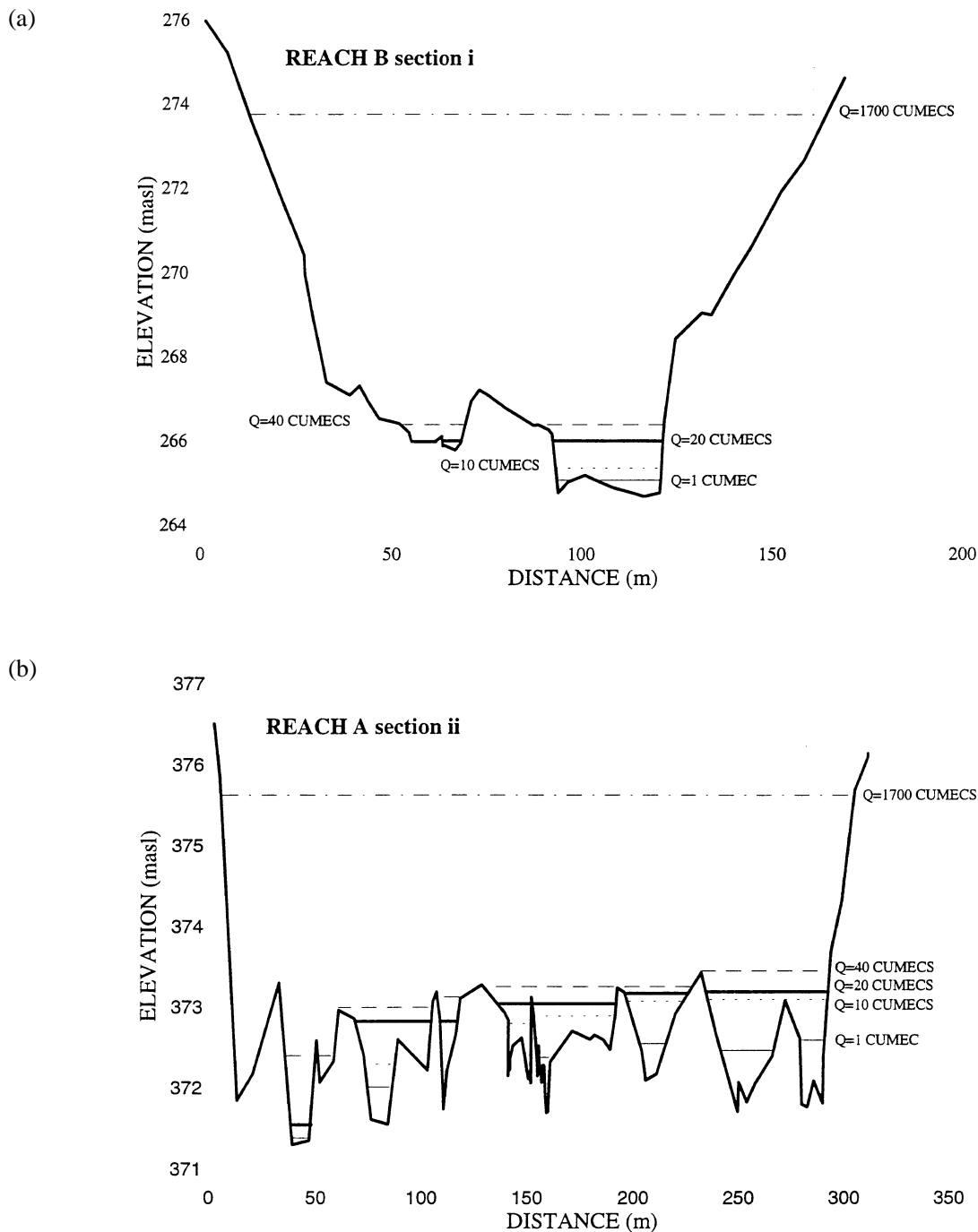


Figure 2. Continuous water surface characteristics of (a) an observed alluvial section (Reach B, section i), compared to (b) the 'stepped' multiple-stage water surface observed for a bedrock-influenced section (Reach A, section ii)

Observational evidence and consideration of the lack of water table suggests that it is very unlikely that a multiple distributary cross-section in a bedrock-influenced area would have a single-stage water surface elevation at any discharge except high-magnitude events. Treatment of these channels as having a continuous, single-stage water surface is erroneous. This is supported by Wohl (1992, 1993), who described bedrock channels on the Burdekin Gorge and the Piccaninny Creek, Australia, as having inner channels and dissected

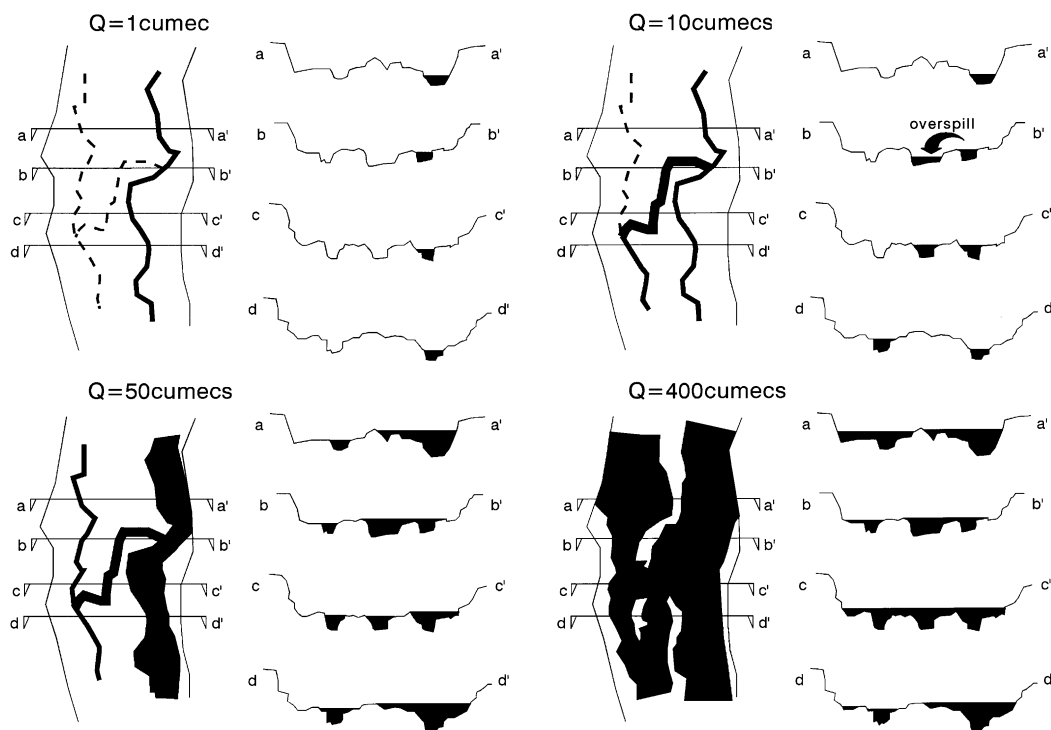


Figure 3. Planform and cross-sectional diagrams of a multiple-distributary bedrock-influenced reach, demonstrating overspill and thresholds for channel distributary activation

bedrock benches with multiple channels that would become active periodically. Although the data collected in the studies of Wohl (1992, 1993) do not allow prediction of stage–discharge relationships for multiple distributaries, Wohl (1992) observes that ‘uncertainties in channel geometry ... water surface elevations, have greater effect’ (on palaeohydraulic reconstruction using a step-backwater method, than altering the specified Manning’s  $n$  resistance), thus acknowledging the importance of accurately modelling channel geometry.

Therefore, as the data used to construct Figure 2 demonstrate, the physical flow characteristics of alluvial and bedrock channels are fundamentally different and these differences have to be addressed. The following sections describe the modelling approaches taken to determine flow dynamics in both alluvial and bedrock-influenced cross-sections and the errors associated with each model.

#### APPROACHES TO MODELLING CHANNEL HYDRAULICS IN ALLUVIAL AND BEDROCK MULTICHANNEL CROSS-SECTIONS

##### *‘Single Stage’ model*

Where the water level across a cross-section is continuous, conventional methods for calculating hydraulic and channel geometry parameters apply and a single rating relationship can be used to characterize the whole cross-section. Where the water surface elevation displays a single stage over multiple distributaries (Figure 2a), the representative cross-sectional channel geometry parameters are the arithmetic sum of the individual distributary parameters. This method is referred to as the ‘Single Stage’ model in this study.

##### *‘Multiple Stage’ model*

Bedrock-influenced reaches do not have a well developed water table, therefore produce a multiple-stage water surface in active distributaries across a cross-section. This is particularly pertinent for the bedrock and mixed anastomosing reaches on the Sabie River, where the  $10 \text{ m}^3 \text{ s}^{-1}$  discharge water surface elevation differed

by over 1.76 m in separate channels (Figure 2b). Therefore, the assumption of a single water surface elevation for a whole cross-section is not realistic and individual channels will have different flow depth to total cross-section discharge relationships. Measurement of stage–discharge relationships for each distributary channel was often logistically or physically prohibitive, yet realistic channel geometry quantification was essential, in order to use the data with confidence when inputting into models of sediment transport or habitat inundations, for example. This necessitated the development of the ‘Multiple Stage’ model, to simulate flow dynamics in this situation.

## CHANNEL GEOMETRY AND HYDRAULIC PARAMETERS MEASURED AT A CROSS-SECTION

Topographic surveys during winter low flows, of numerous cross-sections through two bedrock-influenced reaches, enabled accurate definition of cross-section shape. Measurement of flood flow levels at each distributary channel was not feasible due to the physical inaccessibility of a large proportion of the macro-channel area in the wet season, exacerbated by the presence of dangerous animals out of the river during flood conditions. Therefore, a stage–discharge relationship, over a range of low, medium and high discharges, was obtained only for the active and seasonal channels nearest to the accessible macro-channel bank(s). As the proportion of total discharge in each active distributary was not known, the rating relationships were linked to the total cross-section discharge, that being the sum of the individual distributary discharges, as measured at Kruger and Lower Sabie weirs (Figure 1). The initial water level in each active channel, across a whole cross-section, was surveyed at low, dry season, flow (Figure 2). This demonstrated the deviation from ‘Single Stage’ defined channel geometry.

## DEVELOPMENT OF THE ‘MULTIPLE STAGE’ MODEL

In order to predict flow dynamics for each individual distributary channel, that accounts for the differences in water surface elevations (Figure 2), a ‘Multiple Stage’ model was developed using the available cross-sectional geometry and hydraulic data.

The form of the stage–total cross-section discharge relationship, obtained for an accessible channel at a cross-section, was applied to all of the remaining channels in that section, from the initial, measured elevation (discharge  $1 \text{ m}^3 \text{ s}^{-1}$ , Figure 2). Therefore, all the channels in a cross-section have stage–total cross-section discharge curves of the same gradient, so that the same increase in discharge results in the same increase in stage, but the curves initiate at different elevations. In this way, although the initial water levels of the different channels in a cross-section will vary, their rates of change with discharge will be the same. A limitation to this approach is that it assumes that distributary channels of different shape, size and boundary roughness can be represented by the same stage–discharge relationships. This assumption was justified by the absence of detailed stage–discharge data for all the distributary channels and the need for a preliminary model, in order to provide base data for use in further modelling of channel change or habitat inundation frequencies. A recommendation for future research is to vary the stage–discharge relationships as functions of channel area or wetted perimeter.

Clearly, the model outlined above will only apply to deep, unconnected channels’ yet cross-section profiles for the Sabie River show that the multiple channels combine at high flows, eventually forming a single channel across the whole macro-channel in extreme events (Figure 2). In reality, distinct adjacent channels must join at the same elevation, but the ‘Multiple Stage’ model dictates that one channel will reach the ‘threshold’ point separating it from an adjacent channel at a lower discharge than the adjacent channel(s), as they initially have different water elevations, yet rise with the same gradient. Observations of bedrock distributaries at medium and high flows (Figure 3) have shown that once a channel reaches the elevation ‘threshold’ dividing it from the next, it overflows at the distributary node, contributing excess water into that channel until they are at the same elevation and become one channel.

An idealized account of the ‘Multiple Stage’ model for a typical bedrock anastomosing cross-section is given in Figure 4. For an arbitrary discharge, 1, the initial water levels in the five channels vary. The same rating curve gradient applies to all channels, resulting in the stage at discharge 2, but channel B has reached the topographic overflow threshold to channel A. Therefore, its level remains constant while it contributes its share

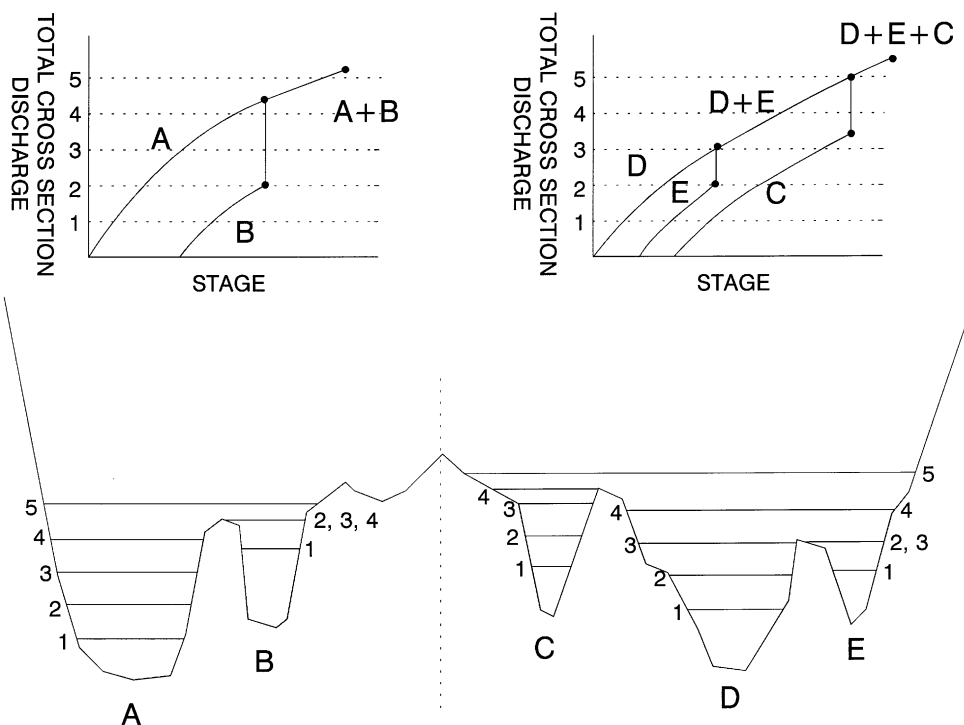


Figure 4. Conceptual diagram of the 'Multiple Stage' model, for use in bedrock-influenced sections, to define stage–cross-section discharge relationships for individual distributaries

of the increase in discharge to channel A via overspill, until the water levels are equal, between discharges 4 and 5. An equivalent interpretation applies to channels C, D and E. Channels E and C reach overspill thresholds, thereby remaining at a stationary stage, until the water level in channel D rises to join with them. The resultant rating curves are shown, with the channel containing the lowest initial water elevation controlling the change in stage with discharge.

Use of this model will ensure a more representative estimation of total channel area or other channel geometry parameters, that being the sum of the separate distributary channel area, over a multiple-channel cross-section. The errors associated with the use of both the 'Single Stage' and the 'Multiple Stage' models, as opposed to the actual channel geometry parameters, are discussed below.

#### ERRORS ASSOCIATED WITH THE 'SINGLE STAGE' AND 'MULTIPLE STAGE' MODELS

In addition to the solitary active distributary rating curve measured per cross-section, seasonal distributary rating curves were observed at several sections within the study reaches, over a range of discharges. These provide a direct test of the 'Multiple Stage' model performance. To define the errors associated with the 'Multiple Stage' and the 'Single Stage' models, when compared to the actual, observed results, an idealized set of rating curves is given (Figure 5). According to the 'Multiple Stage' model, seasonal distributary B will have a rating curve of the same gradient as active distributary A, but will be at a different starting elevation (predicted curve on Figure 5). The shaded area between the observed and predicted rating curves for seasonal distributary B represents the elevation error between the 'Multiple Stage' model prediction and actual, measured elevation. If a continuous 'Single Stage' water surface had been assumed, the error in elevation estimation would have been the 'Multiple Stage' error plus the area between the measured seasonal distributary B rating curve and the measured, active distributary A rating curve.

The 'Single Stage' and 'Multiple Stage' errors have been quantified for several seasonal distributaries (Figures 6 and 7), where rating curves were observed and compared to elevations predicted from assuming the

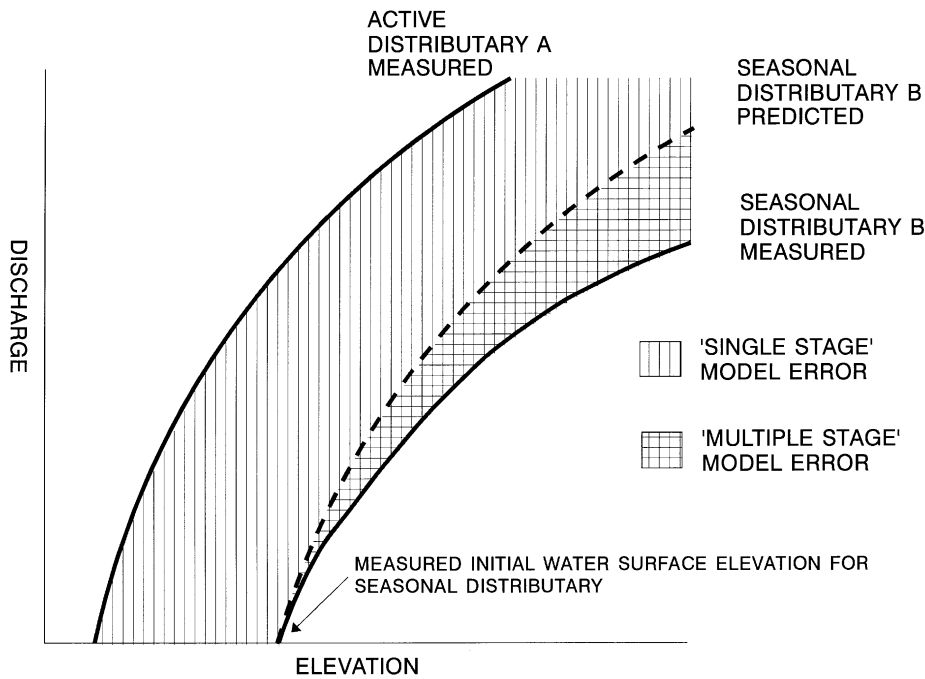


Figure 5. Definition of ‘Multiple Stage’ and ‘Single Stage’ model errors

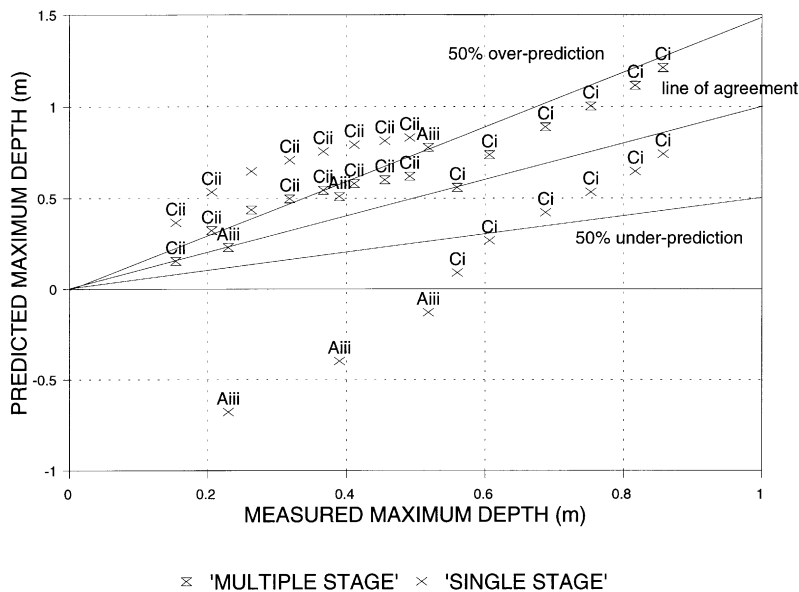


Figure 6. Error between observed, 'Multiple Stage' and 'Single Stage' model predicted maximum depth, over a range of low and medium discharges for several seasonal distributary channels in named cross-sections (see Figure 1 for locations)

gradient of the active channel rating curve represented the seasonal channel (using the ‘Multiple Stage’ model). The maximum depth discrepancy between observed and ‘Multiple Stage’ model was predicted to between 0 per cent and 65 per cent overprediction (Figure 6). This translated to an overprediction error of between 7 per cent and 165 per cent in distributary channel area (Figure 7). The ‘Single Stage’ model predicted negative maximum



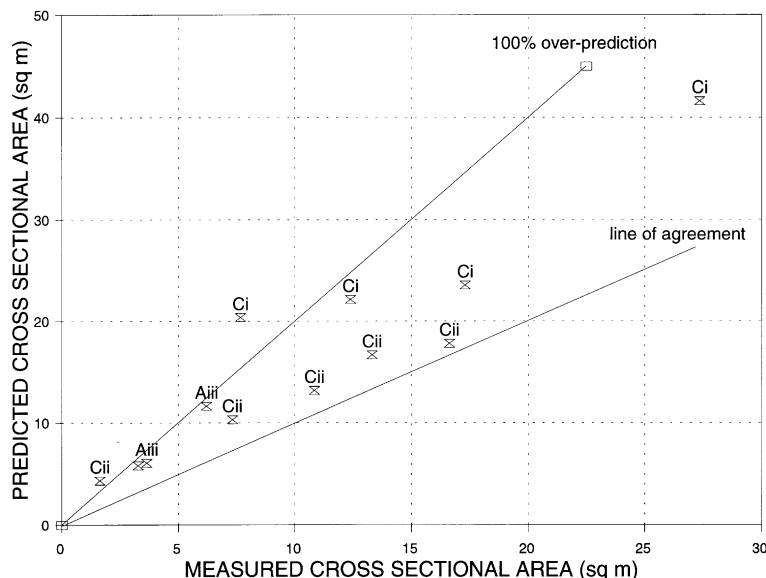


Figure 7. Distributary channel area error between observed and 'Multiple Stage' model predicted over a range of low and medium discharges for several seasonal distributary channels in named cross-sections (see Figure 1 for locations)

depth values for one seasonal channel because the water level in the active channel rating curve, to be used in the 'Multiple Stage' model, was lower than the seasonal channel bed elevation.

These 'Multiple Stage' errors produced are the result of comparison between active channel rating curves, used to drive the 'Multiple Stage' model and the observed seasonal rating curves. Channel characteristics vary between active and seasonal channels, with the latter tending to have mixed alluvial and bedrock and boulder beds, often with a vegetation cover, whereas active channels are generally sediment- and vegetation-free. This will result in different, actual rating curves. Therefore, the 'Multiple Stage' model predictions of channel geometry parameters are likely to be most in error when predicting for seasonal channels and more in agreement when predicting for similar, active channels. Presently, observed rating curves over a range of discharges are not available for multiple active channels in a cross-section, so this hypothesis cannot be tested. However, the errors obtained from use of the 'Multiple Stage' model are well below the corresponding errors produced if the conventional 'Single Stage' model had been used to predict maximum depth in the seasonal channels (Figure 6).

Measurement of the water surface elevation in each distributary channel was possible at a low flow of  $1 \text{ m}^3 \text{ s}^{-1}$ , which enabled errors in the calculation of flow variables to be determined using the 'Single Stage' model, instead of the 'Multiple Stage' model, which in this case equals the measured stage as the low flow elevations were used to run the 'Multiple Stage' model, to be quantified. The errors associated with using the 'Single Stage' model to calculate the average velocity were large (Figure 8). To calculate this error, actual, measured elevations of the water surface in each active distributary were used to determine cross-sectional area and hence velocity, via continuity, for a known discharge. This represents actual average velocity, and equates to the 'Multiple Stage' model at this low discharge. The 'Single Stage' model assumes that the water surface elevation in the active distributary nearest to the macro-channel bank represents the whole cross-section. Therefore, an overestimation of velocity when using the 'Single Stage' model arises when the water surface elevation in the channel nearest to the macrochannel bank is lower than the actual water surface elevations in the remaining active distributaries. As with the maximum depth prediction (Figure 6), the 'Single Stage' model errors in predicting average velocity at  $1 \text{ m}^3 \text{ s}^{-1}$  are very large compared to those measured.

These errors (Figure 8) relate to a single, low discharge and at present the actual error, for total cross-section parameters, between the 'Single Stage' and 'Multiple Stage' models is not available for higher discharges.

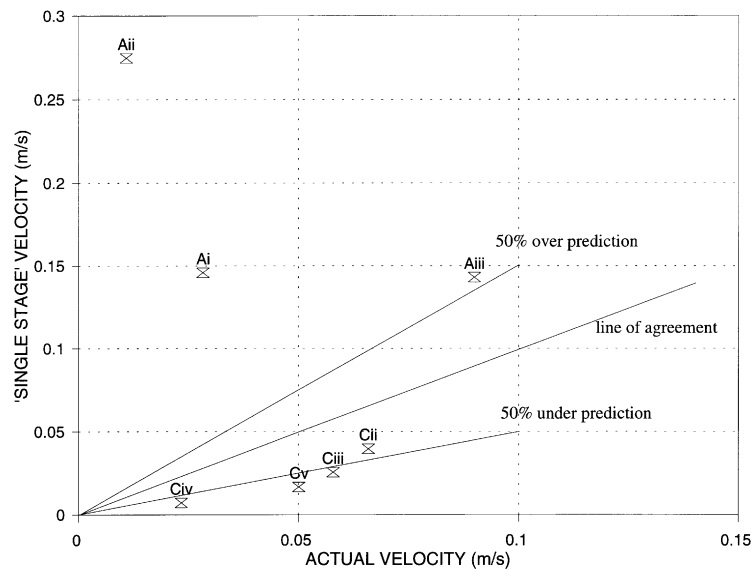


Figure 8. Errors in average velocity calculation at discharge  $1 \text{ m}^3 \text{ s}^{-1}$ , between the 'Single Stage' and the measured, which was used to determine the initial state of the 'Multiple Stage' model for several named cross-sections (see Figure 1 for locations)

However, these low flow errors (Figure 8) will be a maximum, as the error will decrease with increasing discharge, until all the discrete distributaries join and the water surface is continuous and at a single elevation. At this high discharge (from observation, the distributaries at cross-section Aii, for example, join at a discharge of approximately  $700 \text{ m}^3 \text{ s}^{-1}$ ), the 'Single Stage' and 'Multiple Stage' models will then predict equal elevations.

## CONCLUSIONS

The 'Multiple Stage' overspill model represents an attempt to model flow dynamics in multiple-distributary bedrock-influenced river systems (bedrock anastomosing and mixed anastomosing channel types on the Sabie River), where stage–discharge data are not available for every individual distributary channel, by addressing the problem of a discontinuous multiple-stage water surface across a cross-section. The flow geometry variables predicted using the 'Multiple Stage' model provide a substantial improvement on those generated by treating the water surface as continuous, which reflects the conventional approach to calculating hydraulic and geometric parameters. 'Multiple Stage' model predictions of maximum depth were found to overpredict, being between 0 per cent and 65 per cent of the actual observed depth, over a range of discharges in several seasonal distributaries. This compared favourably to 'Single Stage' model predictions, which were over 250 per cent in error. Further improvement in the 'Multiple Stage' model prediction would be likely to be achieved via application of more realistic stage–discharge relationships, those derived as a function of channel area or wetted perimeter for example, for each individual distributary. It is clear from this and other studies that considerable research is required into bedrock-influenced rivers, to further challenge the conventional approaches to defining flow dynamics.

A procedure for use of the 'Multiple Stage' model is as follows.

- (1) Survey the water elevation in each active distributary across the cross-section for a known low flow discharge.
- (2) Subdivide the cross-sections into subsections, separated by highest elevation points or 'thresholds' between the measured active distributaries. In this way, a subsection will comprise one distributary as well as other morphological units such as bedrock core bars or seasonal distributaries.
- (3) Construct a rating curve by observing water surface elevations over a range of total cross-section discharges for one distributary channel.

- (4) Assuming each subsection is independent of adjacent ones, generate rating curves for each distributary by applying the gradient of the measured rating curve to the individual initial, low flow elevation in each distributary. The result will be a series of parallel rating curves with different stages against total cross-section discharge.
- (5) Starting with the distributary containing the highest water surface elevation, determine the points on the rating curve at which the thresholds to both adjacent subsections are exceeded. The stage at the lower of these two points must be kept constant until the adjacent channels' elevations have caught up and the two, then subsequently the three, distributaries join. This process must be completed for all the subsections. The rating curves are thus modified to account for distributaries reaching overspill thresholds and eventually joining into a single channel.
- (6) The resultant distributary rating curves and knowledge of the cross-sectional shape can then be used to calculate cross-sectional or individual distributary geometry and hydraulic parameters.

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